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# Prismatic core high temperature reactor fuel modelling incorporating fuel rotation

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A B S T R A C T

The use of prismatic-core High Temperature Reactors (HTRs), has not yet reached commercialisation, as they are few in operation, and mainly developmental in nature. This work examines numerous models for fuel rotation, thus enhancing and further optimising the fuel lifecycle of a generic HTR. Several rotational scenarios were examined both axially and radially, with radial rotations giving rise to the largest in life extension. Included in the model is a complex analysis of how TRistructural-ISOtropic (TRISO) fuel behaves in operando, increasing the reliably of the model in predicting the benefits of fuel rotation. Finally, an economic assessment was undertaken, which indicted that fuel costs could be reduced by 40.3%, further increasing its economic benefit and efficiency.

## 1. Introduction

It has long been accepted that for a low carbon, reliable energy mix there is a place for nuclear energy (UK, 2016). However, there are two main concerns regarding nuclear energy. Firstly is the funding required for the initial cost of new nuclear plant, as for example, the recently confirmed Hinkley Point C power plant has an estimated construction cost of £18bn (NAO, 2016), with funding from private sources. The second concern is safety, with public concern over such technology rising after the incident at Fukushima in 2011. Combining a lower capital cost with enhanced safety, due to developments in passive safety features, the concept of Small Modular Rectors (SMR) has started to gain growing momentum (Locatelli et al., 2014).

The work presented here examines the impact of fuel element rotation within the core, designed to increase fuel lifetime within the core, thus enhancing its overall economic efficiency. Nuclear fuel rotation is commonly used for refuelling across most power reactors, e.g. the Advanced Gas Cooled Reactors (AGR) which replaces five assembly's a month (Nonbel, 1996) and Light Water Reactors (LWR) where as in the case of Sizewell B one third of the fuel is replaced every 18 months (ONR, 2016). However prismatic core HTR's have not seen this practice implemented. One explanation is down to the lack of commercial HTR's where such fuel life extension could be undertaken, although this process is physically possible. The two major considerations for this work include the economic viability of fuel rotations in the place of using fresh fuel over a reactor lifetime, taking into account the remote nature of planned operation and how it would modify operational parameters.

## 2. Design concept

The design considered is loosely based off the U-Battery (Ding et al., 2011) which aims for a fast deployment using readily available technology, by utilising existing prototypes prismatic core reactors such as Japanese high temperature test rector (HTTR) as a source of reliable and pertinent information. The HTTR has been operating since 1998 allowing for critical parts of the design to be well understood and easy to deploy.

A new core design with the radial and axial design shown in Fig. 1.

The design in Fig. 1 differs significantly from that in the original U-Battery report. This is for two reasons, firstly; this new design focuses on a 10MWth design and secondly; due to the cost and difficulties incurred by using beryllium oxide, the more easily option of graphite is chosen as a side reflector.

## 3. Methodology

In most operational nuclear reactors, fuel is rotated around the core maximising burnup and ensuring the flux across the core is as even as possible. For example, in the AGR, fresh fuel starts at the edges of the active core to increase the flux, and during operation the fuel then moves inwards, increasing burn up. This allows fresh fuel to provide a

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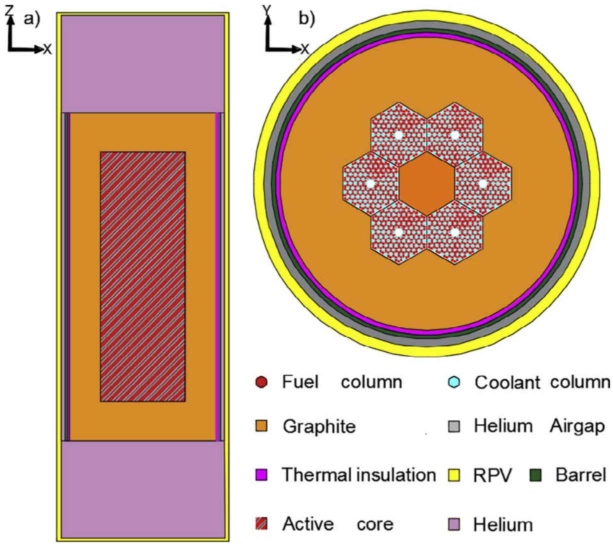


**Fig. 1.** Core layout a) axial schematic of the core. b) Radial representation scaled by a factor of two to highlight the detail.

higher flux of neutrons in the outside of the core where fission is less common than at the centre of the core, where it would require enhanced management to prevent rapid burnup. Such a process allows for higher levels of burnup to be achieved. In the case of HTRs fuel has not traditionally been used in such a manner, primarily due to the nature of the fuel, i.e. either fused into fuel blocks or the process of fuel rotation being too difficult or not economical.

As in the case of the reactor designed there are large amounts of U235 remaining after the first cycle. Our first investigation was to identify those areas where the U235 is not being fully utilised. To model the design, Serpent 2.1.26 was used (Leppänen, 2007), Serpent is a Monte-Carlo based neutronics package using the JEFF 3.1.1 libraries. In this case the TRISO fuel was heterogeneously in the fuel blocks as shown in Fig. 2, each sections contains the same fuel material as in TRISO kernels. The material compositions were then compared after the fuel cycle to further elucidate the changes in fuel composition.

As shown in Fig. 2, the sequence M1 to M21 represents fuel channels which have had their material compositions monitored over a full life cycle within the core. This allows for a radial distribution across the core, in addition to this the M channels are split axially into 10 cm sections, providing a full fuel channel representation. As the fuel composition is directly related to the criticality of the system, as the U235 is depleted, the Monte-Carlo simulation process calculates when the reactor becomes subcritical, shown by the calculated keff, i.e. subcritical being below 1.

To maintain accuracy of the study, yet at a reasonable computational time, the fuel regions had to be split up radially. The methodology for implementing this uses isolines represented in Fig. 3. The

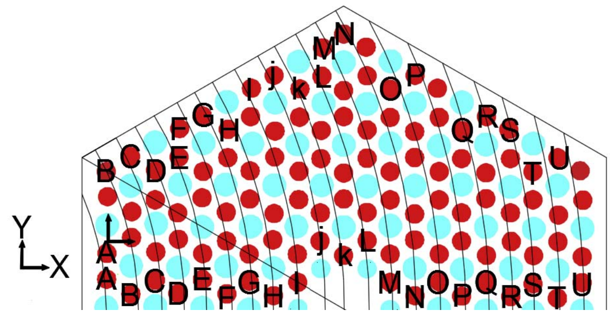

**Fig. 3.** Half a fuel block. The isolines represent the channels with similar burnup. The corresponding letters highlight channels that are assumed to have similar burnup.

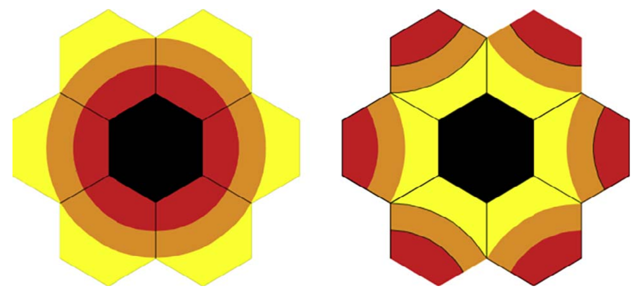

**Fig. 4.** Radial fuel rotation hypotheses.

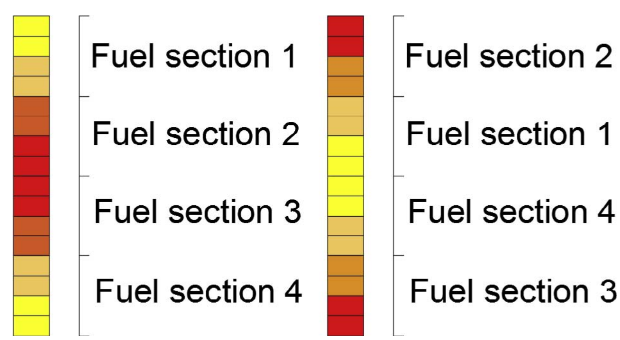


**Fig. 5.** Axial rotation, left initial core burnup and right the rotated version.

**Table 1**
Rotational models used in the simulations of fuel core rotation.

| Z axis | Rotational procedure |
|---|---|
| No rotation | 180 degree rotation<br>60 degrees clockwise |
| Axial rotation | 180 degree rotation<br>60 degrees clockwise |

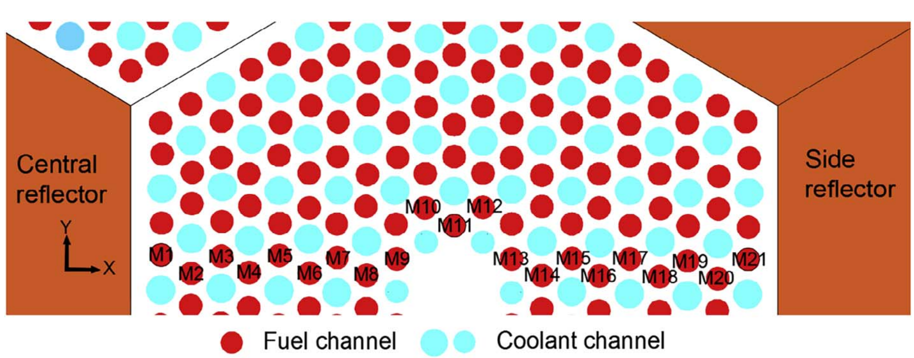


**Fig. 2.** Where M1-21 represents the fuel channels under depletion investigation (Ding et al., 2011).

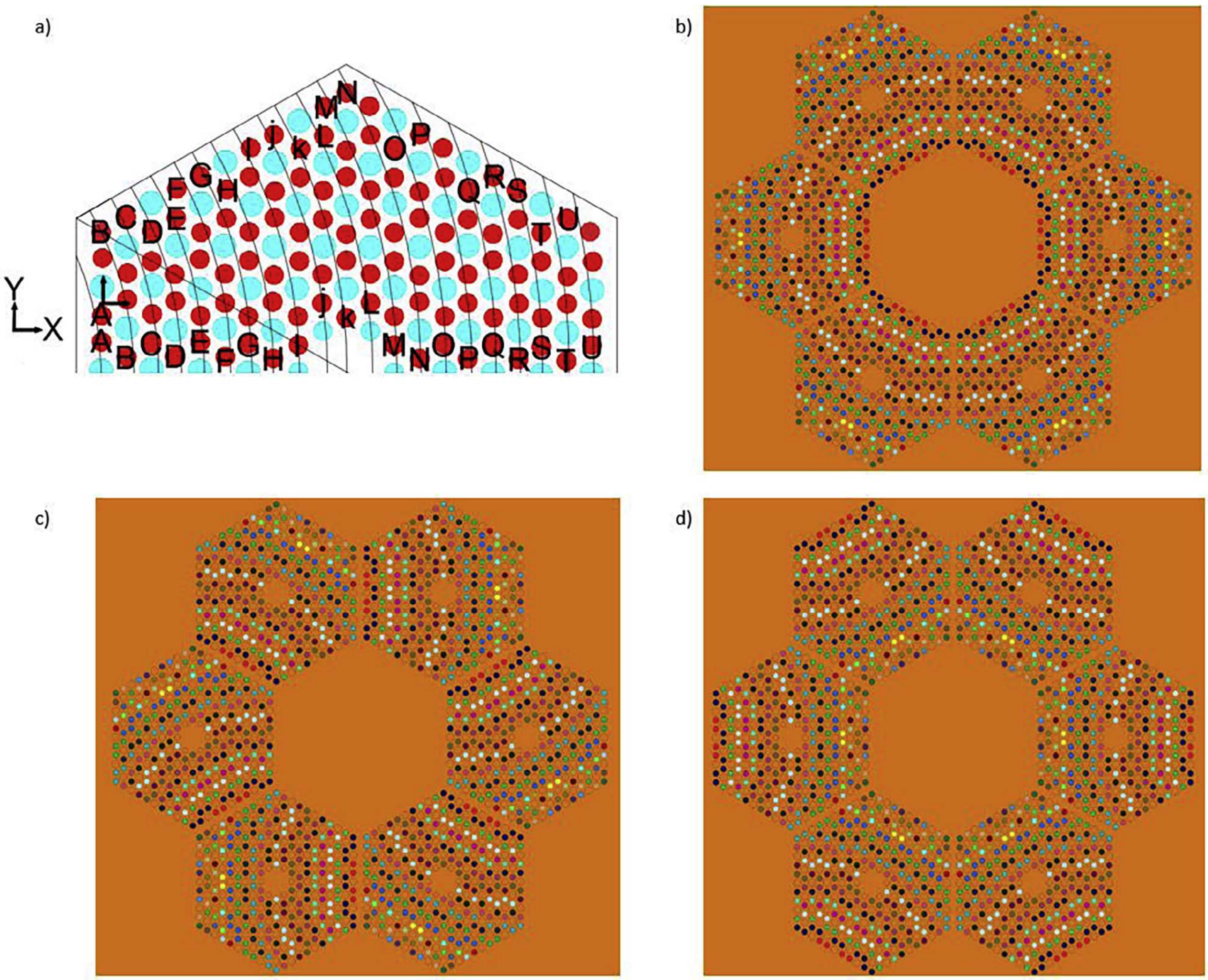


**Fig. 6.** Rotations of the fuel. a) Isolines representation, b) Standard position, c) 60 degree clockwise rotation, d) 180 degree rotation.

**Table 2**
Fuel costs (Ding et al., 2011).

| Costs | M€ |
|---|---|
| Fuel handling costs | 0.5 |
| 264 kg of fuel | 3.2 |

assumption is that the radial burnup would be similar across these isolines due to the symmetry of the core. If the isoline assumption was correct, the centre letter should reach a similar material depletion to the furthest fuel channel on the isoline. The second study tested this theory by comparing a ratio of the axially averaged averaging depletion across each of the letters shown in Fig. 3.

The fuel pins at the back four points, U, T, S and R were modelled individually, allowing for maximum accuracy of the rotational process to account for loss of symmetry across the fuel block.

The reactor consists of six fuel blocks placed around a central reflector. Each fuel block is 80 cm in height with 36 cm across each block. Thus the total height of the active core is 320 cm and 108 cm wide, these measurements make the core thin and tall. This paper aims to identify the best methods to increase the lifetime of the reactor by utilising fuel rotation. Previous studies on PWR's (Laboratory, 2002) (Manolova et al., 2005) have highlighted the importance of increasing the axial burnup through the design of the core or operating conditions. From a radial perspective, the centre of the core is often depictured as

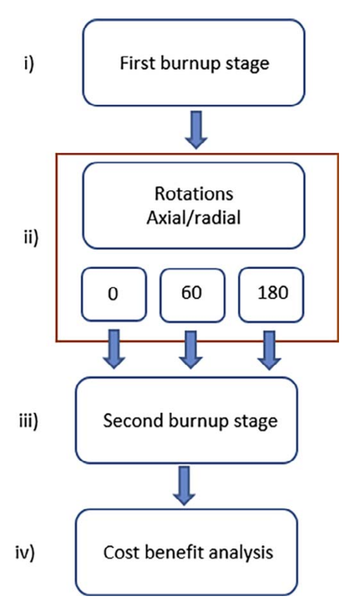


**Fig. 7.** Step by step process of stages undertaken.

having the highest power profile, which directly relates to the burnup of the fuel. With this design, the annular central reflector positioning aims to increase the thermal flux in the centre of the core and thus

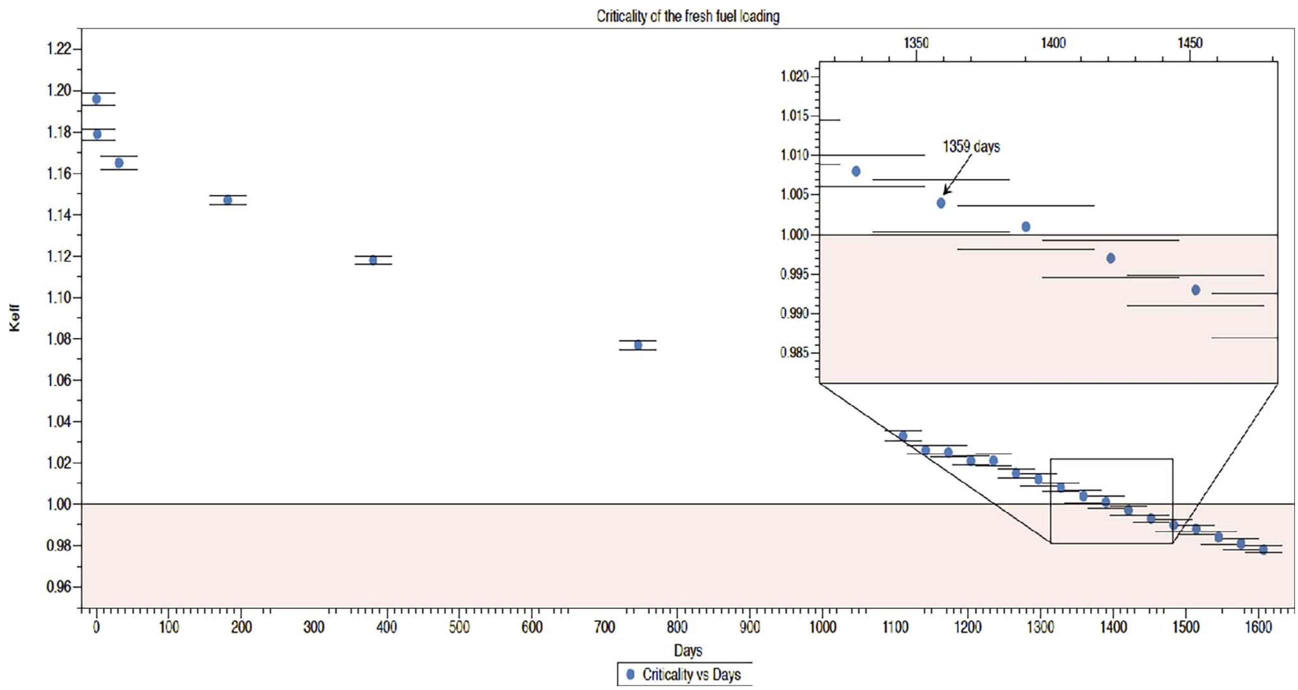


**Fig. 8.** Criticality as function of time within the core, error bars are set at 95% of confidence, with the shaded area representing a non-critical system.

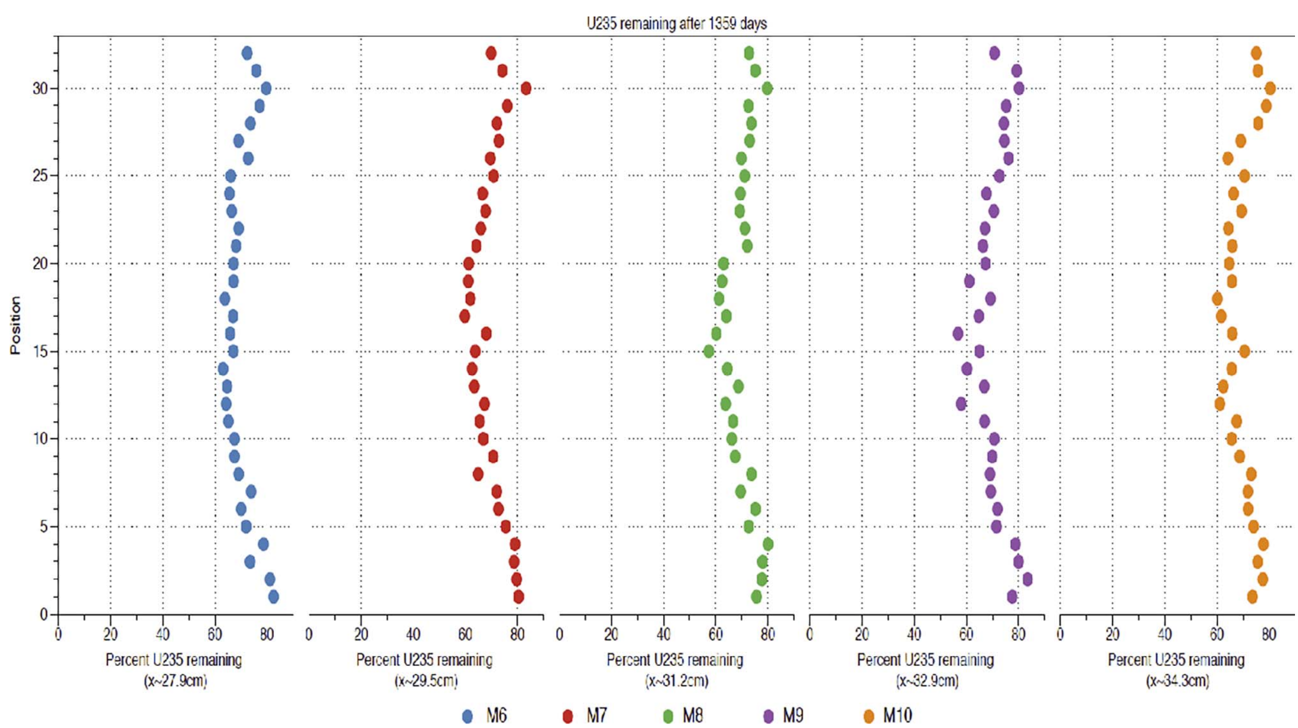


**Fig. 9.** Material compositions of of M6-M10.

should provide the highest thermal flux within this region.

To increase burnup, and thus overall economic efficiency, rotation of fuel blocks was examined. The design consists of 24 fuel blocks, placed around the central reflector, and are designed to burn symmetrically from the centre outwards. The highest burnup was therefore designed to occur at the centre where the neutrons are easily transferred between fuel blocks and the moderation is highest both increasing burnup, shown in Fig. 4. Despite the core being made of graphite with varying density, burn up was expected to radially decrease going outwards. Coupled to this was the assumption that axial burnup would be highest at the centre of the core, with concomitant decrease the further the fuel was from the centre point. This led to the hypothesis that fuel blocks could be rotated axially and radially to allow for lower burn up sections to be moved to the centre, thus increasing the utilisation of the U235 most effectively, shown in Figs. 4 and 5.

The fuelling machine (FM) would be attached to the top of the reactor core, and using a central channel would fully access the entire core allowing for access to each individual fuel block. Since one concern with fuel rotation is increasing the operating costs, a full cost benefit analysis would determine if the process is economically viable.

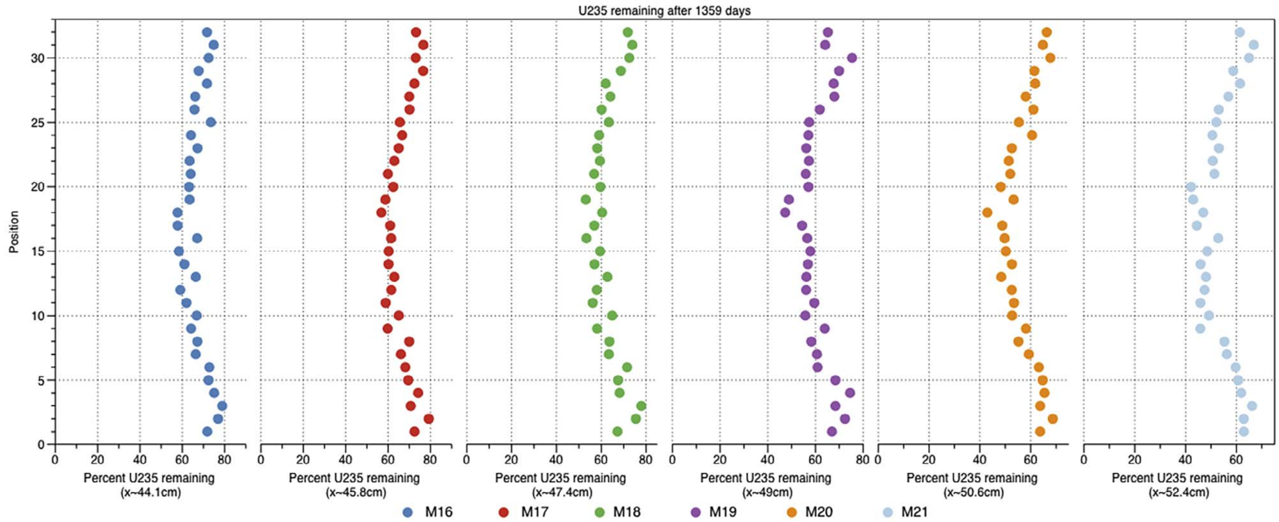


**Fig. 10.** Material compositions of M16-M21.

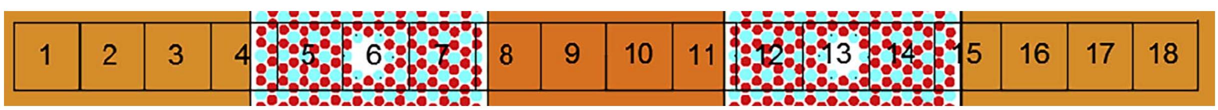


**Fig. 11.** Detector positions.

**Table 3**
Stages chosen for switching.

| Stages | Days | Years | Burnup (MWd/KgU) |
|---|---|---|---|
| 1 | 746 | 2 | 32.07 |
| 2 | 1111 | 3 | 47.76 |
| 3 | 1328 | 3.72 | 58.42 |

Due to the differing nature of potential rotation, four different rotational models were investigated, shown in Table 1.

The initial loading looks at a simple core layout, shown in Fig. 6(a), where the total packing factor in every block is the same and equal to 29%. The simulation then burns the fuel until criticality reduces to below unity, i.e. no longer self-sustaining. At this point the end of cycle has been determined, leading to the next stage where the periods of rotation were isolated (see Table 2).

Two key features in Serpent were used for this, initially a simple universal transformation (utrans) was used to rotate part of the core on the Z axis. The second option was to record material composition after each burnup stage, and then manipulate these compositions location to achieve axial transformation.

The methods used to identify the rotation were considered in reactor-day extension from the initial start, coupled with the overall cost saving over the lifetime of the reactor. Costs included in the U-Battery conceptual design were used and compared these included;

The costs were based on those proposed in the initial design and scaled accordingly to allow for a comparison to be made, it is important to note that the costs for reloading the fuel are not included in the initial report. Consequently fuel handling costs are assumed to be the cost of transporting the new fuel to site, and loading into the core. Thus the same value was assumed for moving the fuel to site despite this potentially being estimated, and not realistic. However, with lifetime extension these costs would be reduced, as less fuel movement is required. A further key assumption was the reactor performing for the full expectancy of 60 years as stated in the initial design criteria. After the initial cycle, decisions on how to rotate the fuel and what benefits arose were considered, with further simulations identifying the maximum extension that could be added due to the rotation.

Fig. 7 goes through the stages to obtain the most beneficial rotation method. The initial burnup step (i) identifies the time the reactor can run before any intervention is required. This stage is used to calculate the maximum effective full power days.

Fuel rotation is step (ii), before a further burnup is simulated in stage (iii) with simulation being completed when criticality is no longer reached. It is at this point the reactors fuel will require a new loading of fuel.

A cost benefit analysis (iv) examines both the operational costs and risks involved with fuel manipulation. It is a simple method, but one in which the financial benefit for such rotation can be estimated.

## 4. Results and discussion

The initial study simulated an unbound criticality test, to examine the lifetime of the reactor, purely through determination of when Keff is no longer above 1, i.e. no longer critical.

As can be seen in Fig. 8 the reactor is predicted to remain critical for ~1359 day under the conditions of the simulation. Following this fuel compositions were taken axially across M1-21, focusing on the U235 content in these 21 fuel rods. An exemplar is shown in Fig. 9, where the % of U235 remaining is shown as a function of channel.

Fig. 9 looks into the depleted U235 across each of the sections M6-M10 of the core in the fuel channels identified by Fig. 2. Using the results from this initial simulation, the axial areas identified as the most depleted will be moved to the outer extremities of the core. Thus following this rotation the channels reverse such that in M21 in Fig. 2, becomes M1, as can be seen in Fig. 6.

The positions towards the centre of the core, positions 10–20, contain a significant reduction in U235, particularly when compared to the other fuel channels. However, the peaks in % U235 remaining are ~30 cm from the top/bottom of the active core. This arises from the extremities of the core benefitting from the reflector at the top/bottom, which aids fission at the top/bottom. However, at the centre of the fuel blocks such beneficial effects are reduced, indicating that for a reflector to be effective there needs to be a high enough flux that utilises the reflectors.

**Table 4**
Criticality of none axially rotated systems.

| Days extended | End of life | | | | Three years | | | | Two years | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 180 degrees | Standard relative error | Clockwise | Standard relative error | 180 degrees | Standard relative error | Clockwise | Standard relative error | 180 degrees | Standard relative error | Clockwise | Standard relative error | Days extended continued | 180 degrees | Standard relative error | Clockwise | Standard relative error |
| 0 | 1.0080 | 0.0021 | 1.0059 | 0.0015 | 1.0347 | 0.0012 | 1.0344 | 0.0011 | 1.0763 | 0.0016 | 1.0764 | 0.0010 | 1264 | 1.0142 | 0.0017 | 1.0120 | 0.0010 |
| 1 | 1.0113 | 0.0012 | 1.0098 | 0.0022 | 1.0373 | 0.0011 | 1.0393 | 0.0016 | 1.0805 | 0.0013 | 1.0803 | 0.0015 | 1295 | 1.0091 | 0.0015 | 1.0121 | 0.0013 |
| 183 | 1.0131 | 0.0013 | 1.0109 | 0.0016 | 1.0372 | 0.0012 | 1.0392 | 0.0014 | 1.0731 | 0.0010 | 1.0732 | 0.0010 | 1326 | 1.0097 | 0.0017 | 1.0111 | 0.0014 |
| 365 | 1.0085 | 0.0009 | 1.0103 | 0.0015 | 1.0387 | 0.0016 | 1.0394 | 0.0013 | 1.0641 | 0.0014 | 1.0621 | 0.0016 | 1357 | 1.0079 | 0.0013 | 1.0081 | 0.0012 |
| 396 | 1.0083 | 0.0014 | 1.0078 | 0.0015 | 1.0364 | 0.0016 | 1.0341 | 0.0013 | 1.0598 | 0.0014 | 1.0598 | 0.0016 | 1388 | 1.0070 | 0.0015 | 1.0044 | 0.0016 |
| 427 | 1.0081 | 0.0009 | 1.0064 | 0.0016 | 1.0339 | 0.0015 | 1.0356 | 0.0014 | 1.0580 | 0.0011 | 1.0574 | 0.0013 | 1419 | 1.0022 | 0.0015 | 1.0010 | 0.0016 |
| 458 | 1.0052 | 0.0012 | 1.0065 | 0.0015 | 1.0331 | 0.0014 | 1.0326 | 0.0015 | 1.0577 | 0.0011 | 1.0572 | 0.0015 | 1450 | 1.0030 | 0.0013 | 1.0023 | 0.0015 |
| 489 | 1.0019 | 0.0019 | 1.0019 | 0.0014 | 1.0296 | 0.0014 | 1.0301 | 0.0016 | 1.0544 | 0.0016 | 1.0543 | 0.0014 | 1481 | 1.0005 | 0.0010 | | |
| 520 | 1.0031 | 0.0012 | 1.0008 | 0.0017 | 1.0270 | 0.0014 | 1.0303 | 0.0016 | 1.0527 | 0.0014 | 1.0536 | 0.0012 | 1512 | 0.9969 | 0.0015 | | |
| 551 | 1.0007 | 0.0016 | 0.9985 | 0.0016 | 1.0272 | 0.0011 | 1.0302 | 0.0014 | 1.0514 | 0.0017 | 1.0509 | 0.0018 | 1543 | 0.9987 | 0.0013 | | |
| 582 | 0.9983 | 0.0014 | 0.9996 | 0.0013 | 1.0275 | 0.0013 | 1.0266 | 0.0012 | 1.0501 | 0.0016 | 1.0501 | 0.0012 | 1544 | 0.9947 | 0.0014 | | |
| 613 | 0.9982 | 0.0016 | 0.9997 | 0.0014 | 1.0239 | 0.0013 | 1.0225 | 0.0014 | 1.0462 | 0.0014 | 1.0464 | 0.0012 | | | | | |
| 644 | 0.9954 | 0.0010 | 0.9933 | 0.0016 | 1.0237 | 0.0012 | 1.0215 | 0.0018 | 1.0470 | 0.0007 | 1.0491 | 0.0011 | | | | | |
| 675 | 0.9941 | 0.0010 | 0.9925 | 0.0015 | 1.0219 | 0.0017 | 1.0193 | 0.0015 | 1.0436 | 0.0012 | 1.0446 | 0.0010 | | | | | |
| 706 | 0.9941 | 0.0011 | 0.9913 | 0.0013 | 1.0187 | 0.0016 | 1.0167 | 0.0015 | 1.0425 | 0.0014 | 1.0429 | 0.0014 | | | | | |
| 737 | 0.9888 | 0.0012 | 0.9910 | 0.0013 | 1.0168 | 0.0012 | 1.0155 | 0.0011 | 1.0419 | 0.0013 | 1.0416 | 0.0010 | | | | | |
| 768 | | | 0.9875 | 0.0017 | 1.0155 | 0.0015 | 1.0164 | 0.0010 | 1.0403 | 0.0015 | 1.0385 | 0.0011 | | | | | |
| 799 | | | 0.9901 | 0.0019 | 1.0142 | 0.0012 | 1.0145 | 0.0018 | 1.0371 | 0.0015 | 1.0352 | 0.0018 | | | | | |
| 830 | | | 0.9848 | 0.0015 | 1.0135 | 0.0013 | 1.0106 | 0.0010 | 1.0349 | 0.0016 | 1.0381 | 0.0012 | | | | | |
| 861 | | | 0.9855 | 0.0015 | 1.0104 | 0.0012 | 1.0091 | 0.0013 | 1.0323 | 0.0017 | 1.0351 | 0.0015 | | | | | |
| 892 | | | 0.9837 | 0.0017 | 1.0068 | 0.0014 | 1.0113 | 0.0015 | 1.0327 | 0.0012 | 1.0315 | 0.0010 | | | | | |
| 923 | | | 0.9791 | 0.0015 | 1.0085 | 0.0014 | 1.0071 | 0.0011 | 1.0293 | 0.0011 | 1.0292 | 0.0013 | | | | | |
| 954 | | | 0.9782 | 0.0009 | 1.0044 | 0.0022 | 1.0051 | 0.0011 | 1.0292 | 0.0013 | 1.0314 | 0.0011 | | | | | |
| 985 | | | 0.9773 | 0.0010 | 1.0054 | 0.0013 | 1.0033 | 0.0016 | 1.0259 | 0.0012 | 1.0276 | 0.0017 | | | | | |
| 1016 | | | 0.9734 | 0.0016 | 1.0006 | 0.0014 | 1.0010 | 0.0019 | 1.0278 | 0.0017 | 1.0247 | 0.0008 | | | | | |
| 1047 | | | 0.9723 | 0.0016 | 1.0011 | 0.0012 | 1.0005 | 0.0011 | 1.0230 | 0.0014 | 1.0272 | 0.0018 | | | | | |
| 1078 | | | 0.9740 | 0.0012 | 0.9972 | 0.0016 | 1.0003 | 0.0010 | 1.0261 | 0.0015 | 1.0204 | 0.0015 | | | | | |
| 1109 | | | 0.9695 | 0.0012 | 0.9971 | 0.0022 | 0.9975 | 0.0014 | 1.0224 | 0.0012 | 1.0225 | 0.0015 | | | | | |
| 1140 | | | | | | 0.9963 | 0.0014 | 0.9960 | 1.0207 | 0.0013 | 1.0170 | 0.0016 | | | | | |
| 1171 | | | | | | 0.9954 | 0.0014 | 0.9943 | 1.0168 | 0.0014 | 1.0174 | 0.0012 | | | | | |
| 1202 | | | | | | 0.9909 | 0.0013 | 0.9922 | 1.0149 | 0.0017 | 1.0147 | 0.0015 | | | | | |
| 1233 | | | | | | 0.9894 | 0.0015 | 0.9904 | 1.0122 | 0.0012 | 1.0149 | 0.0009 | | | | | |

**Table 5**
Life time extensions of the axially rotated options.

| Days extended | End of life | | | | Three years | | | | Two years | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 180 degrees | Standard relative error | Clockwise | Standard relative error | 180 degrees | Standard relative error | Clockwise | Standard relative error | Days extended | 180 degrees | Standard relative error | Clockwise | Standard relative error |
| 0 | 1.0280 | 0.0011 | 1.0282 | 0.0013 | 1.0481 | 0.0011 | 1.0506 | 0.0017 | 0 | 1.0898 | 0.0011 | 1.0890 | 0.0017 |
| 1 | 1.0245 | 0.0012 | 1.0248 | 0.0020 | 1.0495 | 0.0016 | 1.0488 | 0.0018 | 1 | 1.0882 | 0.0013 | 1.0872 | 0.0016 |
| 183 | 1.0204 | 0.0019 | 1.0226 | 0.0014 | 1.0460 | 0.0012 | 1.0433 | 0.0013 | 183 | 1.0645 | 0.0011 | 1.0662 | 0.0013 |
| 365 | 1.0188 | 0.0013 | 1.0192 | 0.0016 | 1.0410 | 0.0013 | 1.0428 | 0.0013 | 365 | 1.0409 | 0.0015 | 1.0408 | 0.0009 |
| 396 | 1.0150 | 0.0015 | 1.0126 | 0.0017 | 1.0360 | 0.0014 | 1.0341 | 0.0018 | 396 | 1.0368 | 0.0012 | 1.0370 | 0.0012 |
| 427 | 1.0091 | 0.0011 | 1.0114 | 0.0011 | 1.0308 | 0.0010 | 1.0315 | 0.0018 | 427 | 1.0356 | 0.0017 | 1.0330 | 0.0016 |
| 458 | 1.0056 | 0.0016 | 1.0061 | 0.0014 | 1.0274 | 0.0015 | 1.0272 | 0.0013 | 458 | 1.0302 | 0.0006 | 1.0281 | 0.0012 |
| 489 | 1.0002 | 0.0013 | 1.0043 | 0.0017 | 1.0240 | 0.0008 | 1.0253 | 0.0012 | 489 | 1.0277 | 0.0009 | 1.0261 | 0.0015 |
| 520 | 0.9991 | 0.0015 | 1.0002 | 0.0010 | 1.0208 | 0.0013 | 1.0184 | 0.0016 | 520 | 1.0201 | 0.0016 | 1.0233 | 0.0014 |
| 551 | 0.9940 | 0.0018 | 0.9931 | 0.0010 | 1.0174 | 0.0014 | 1.0162 | 0.0014 | 551 | 1.0196 | 0.0015 | 1.0196 | 0.0017 |
| 582 | 0.9906 | 0.0012 | 0.9873 | 0.0014 | 1.0119 | 0.0012 | 1.0112 | 0.0016 | 582 | 1.0157 | 0.0016 | 1.0161 | 0.0012 |
| 613 | 0.9860 | 0.0010 | 0.9874 | 0.0013 | 1.0087 | 0.0016 | 1.0097 | 0.0012 | 613 | 1.0106 | 0.0010 | 1.0104 | 0.0014 |
| 644 | 0.9838 | 0.0012 | 0.9839 | 0.0011 | 1.0050 | 0.0013 | 1.0054 | 0.0016 | 644 | 1.0073 | 0.0010 | 1.0072 | 0.0011 |
| 675 | 0.9772 | 0.0011 | 0.9800 | 0.0014 | 1.0024 | 0.0017 | 1.0027 | 0.0015 | 675 | 1.0039 | 0.0015 | 1.0034 | 0.0012 |
| 706 | 0.9774 | 0.0010 | 0.9769 | 0.0015 | 0.9970 | 0.0014 | 0.9959 | 0.0011 | 706 | 1.0005 | 0.0012 | 0.9998 | 0.0014 |
| 737 | 0.9701 | 0.0014 | 0.9733 | 0.0012 | 0.9945 | 0.0012 | | | 737 | 0.9973 | 0.0011 | 0.9981 | 0.0015 |
| 768 | 0.9671 | 0.0014 | 0.9667 | 0.0015 | 0.9917 | 0.0015 | | | | | | | |

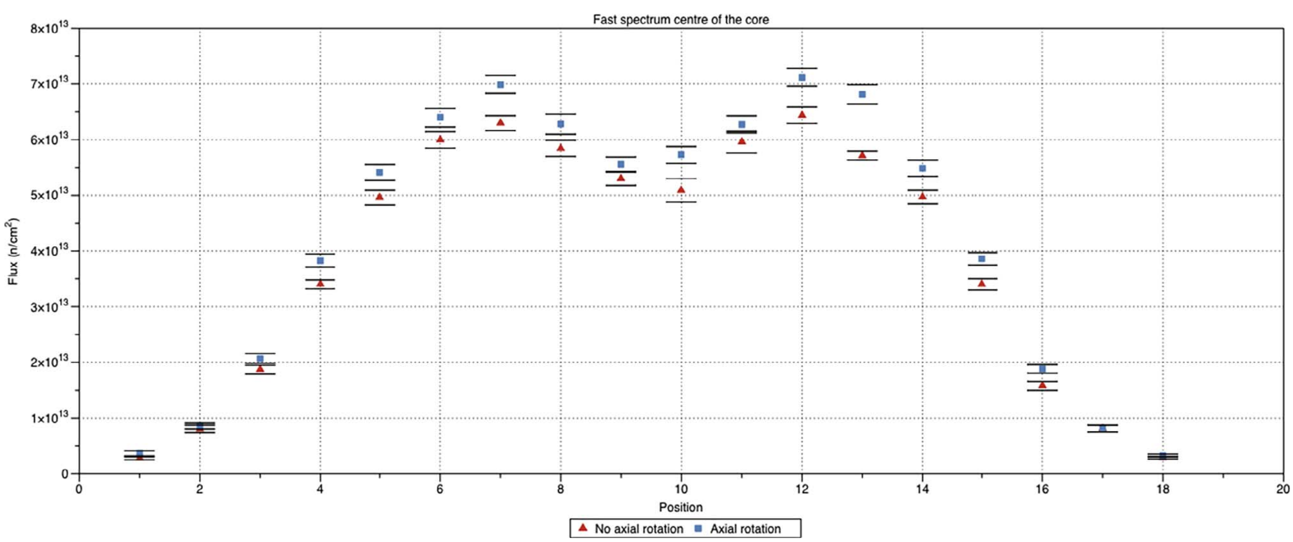


**Fig. 12.** Fast flux from the centre of the core 0.4 eV–20 MeV.

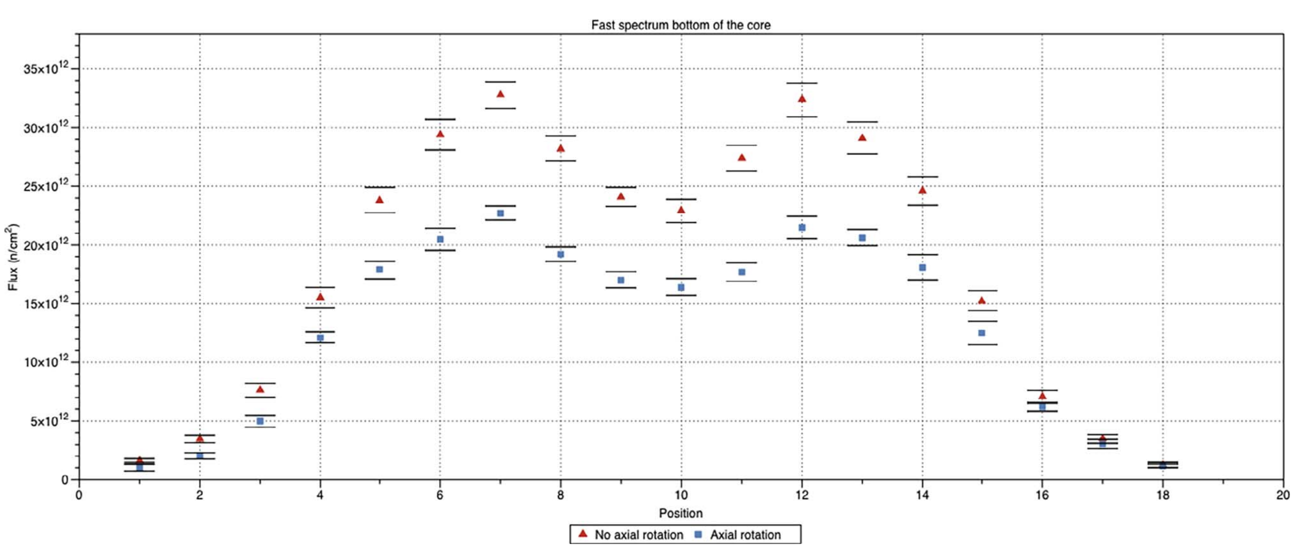


**Fig. 13.** Fast flux at the bottom of the core at 0.4 eV–20 MeV.

**Table 6**
Cost benefit analysis of not axially fuel rotated.

| None axial rotation | Rotation | Days before first interaction | Days extended through rotation | Total lifetime | Total lifetime years | Total fuel costs per day (€) | Amount of refuels | Total cost of fuel | Number of reshuffles | Total cost of reshuffles | Total cost |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 years | 180 degrees | 746 | 1481 | 2227 | 6.1 | 1454.79 | 9.83 | €31.9M | 19.67 | €9.8M | €41.7M |
| | clockwise | 746 | 1481 | 2227 | 6.1 | 1454.79 | 9.83 | €31.9M | 19.67 | €9.8M | €41.7M |
| 3 years | 180 degrees | 1111 | 745 | 1856 | 5.08 | 1745.59 | 11.8 | €38.2M | 23.6 | €11.8M | €50.0M |
| | clockwise | 1111 | 652 | 1763 | 4.83 | 1837.67 | 12.42 | €40.2M | 24.84 | €12.4M | €52.7M |
| End of life | 180 degrees | 1328 | 249 | 1577 | 4.32 | 2054.42 | 13.89 | €45.0M | 27.77 | €13.9M | €58.9M |
| | clockwise | 1328 | 218 | 1546 | 4.24 | 2095.61 | 14.17 | €45.9M | 28.33 | €14.2M | €60.1M |
| Direct refuel | N/a | 1328 | 0 | 1328 | 3.64 | 2439.62 | 16.49 | €53.4M | 32.98 | €16.5M | €69.9M |

**Table 7**
Cost benefit analysis of the axially rotated fuel reshuffling.

| Axial rotation | Rotation | Days before first interaction | Days extended through rotation | Total lifetime | Total lifetime years | Total fuel costs per day (€) | Amount of refuels | Total cost of fuel | Number of reshuffles | Total cost of reshuffles | Total cost |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 years | 180 degrees | 746 | 706 | 1452 | 3.98 | 2231.28 | 15.08 | €48.9M | 30.17 | €15.1M | €63.9M |
| | clockwise | 746 | 706 | 1452 | 3.98 | 2231.28 | 15.08 | €48.9M | 30.17 | €15.1M | €63.9M |
| 3 years | 180 degrees | 1111 | 373 | 1484 | 4.07 | 2183.16 | 14.76 | €47.8M | 29.51 | €14.8M | €62.6M |
| | clockwise | 1111 | 404 | 1515 | 4.15 | 2138.49 | 14.46 | €46.8M | 28.91 | €14.5M | €61.3M |
| End of life | 180 degrees | 1328 | 187 | 1515 | 4.15 | 2138.49 | 14.46 | €46.8M | 28.91 | €14.5M | €61.3M |
| | clockwise | 1328 | 187 | 1515 | 4.15 | 2138.49 | 14.46 | €46.8M | 28.91 | €14.5M | €61.3M |
| Direct refuel | N/a | 1328 | 0 | 1328 | 3.64 | 2439.62 | 16.49 | €53.4M | 32.98 | €16.5M | €69.9M |

Fig. 10 shows the fuels at the very edge of the core, these have the additional benefit of being surrounded by the most moderating material. M20 and 21 are showing a significantly higher burnup than that at the centre, M6. This implies that the side reflector is having significant implications on the burnup of the fuel channels furthest from the centre of the core (see Fig. 11).

The increase in burnup at the centre is primarily due to additional flux contribution arising from areas close to the centre. Due to the isotropic nature of fission there remains a high probability of neutrons returning into the core from outside as there is the neutron leaving the centre. Consequently, this can cause the centre of the core to burn up faster than the exterior. Coupled with this the central reflector plays a key role with neutrons thermalizing rapidly at the centre of the core.

In order to estimate optimal time for fuel rotation, different durations were used. The rotation stages are outlined in Table 3.

These stages were chosen as they are far enough from the initial commissioning to not to cause too much disruption to reactor operation. A duration of two years approximates to half of the estimated final burn up, thus designed to yield increased burn up after rotation.

Examination of material composition radially after 1359 days in the core, which would traditionally be termed the end of life for the core, and comparing gives rise to an average method for comparison. The material compositions of each mirroring 10 cm axial section previously shown in Fig. 3 are compared to each other such via a ratio and then averaged across the fuel channel and the maximum deviation across an isoline was 2.5% over the lifecycle of the fuel, indicating the isoline representation was accurate.

The rotation is split into two stages in Tables 4 and 5. The first stage does not include axial rotation, just movement, as shown in Fig. 6.

The results from such movement shows a high level of consistency, with method giving rise to a similar level of expected life extension, the results are shown in Table 4. Table 4 looks into rotating the fuel at different points in time, with the years at the top of the graph the time the rotation is implemented. However, a 180 degree rotation would have been expected to experience a higher degree of burn up in the centre after rotation. This implies however, that as long as the quantity of U235 remains high in the centre of the core, life extension is possible.

With axial rotation however, there was observed a significantly reduced life extension, contradicting the initial hypothesis. One potential cause could be from a reduced neutron contribution during operation, from the U235 being depleted, thus reducing the axial contribution when rotated. To test this hypothesis the flux was monitored after the rotation at both the bottom of the core and the centre of the 180 degree rotations. The flux is recorded using a detector in Serpent, these detectors are 10 cm cubic shapes positioned across the core as depictured by Fig. 10. This would then identify the main cause for difference in the two rotation models.

The longest life extension would be expected to arise from a balanced burn up of fuel through fuel rotation, as shown in Table 4. This would then create an effective fuel lifetime of six years, which exceeds that required in the initial design brief. However, the initial hypothesis regarding the axial rotation providing the highest life extension has been shown to be incorrect.

Examination of expected fluxes, shown in Figs. 12 and 13, provides insight into why when the centre of the cores fast flux, representing U235 undergoing fission, is examined. The axial rotation gains a slightly higher flux at the centre of the core due to the freshest fuel being placed into the centre. However, such fluxes at the bottom of the core in Fig. 13 highlight the impact of axial rotation which significantly lowers the burn which identifies that rotation is reducing fission rate. With the combination of Figs. 12 and 13, it is noted that there is only a small increase in flux in the centre of the core, compared to a significant drop in flux at the edges. This directly affects the criticality as the depleted materials at the edge of the core are having a higher parasitic effect on the overall criticality of the system, compared to the small benefit to that of the flux in the centre.

Fig. 10 has shown that there is a higher amount of depleted fuel at the edges of the fuel block, this implies that the 180 degree rotation specifically benefits from moving the fresher fuel from M6 in Fig. 9 into the centre. This allows for the external fuel blocks to contribute to a higher degree after the rotation.

Placing more fuel at the edges of the core would provide a higher effect of neutrons being passed back into the centre of the core axially. This then implies that increasing the packing factor of the top and bottom core, will in turn enable an extended lifetime extension and potentially higher burn up in all sectors.

Due to the small size of the design such rotational options of fuel blocks is limited which gives rise to the symmetrical burnup seen in Fig. 9. This benefit might not be found if the active core was wider due to the impact of the side reflectors now being less. As seen in Fig. 9 the axial increased burnup from reflectors, contributes up to 30 cm into the core, thus covering just over half of the radial fuel block dimensions hence, giving rise to symmetrical burnup.

From a rotational point of view, where the earlier the rotation the longer the fuel life cycle, is problematic, as the core now requires a FM to be required more frequently. From an operational perspective the cost of a FM would need to be considered.

Financially the most economical approach is a simple rotation after two years, which is also the least technically challenging. The initial lifetime cost of the fuel in the core was estimated to be €69.9mn based on the direct refuel scenario in Table 6. It was found that the most cost effective fuel rotation scenario was in Table 7, with an initial two year fuel rotation, reducing the total fuel cost to €41.7mn, an overall saving of 40.3%. This cost saving could then allow an additional €1mn per fuel reload to be allocated to help offset any risk with the procedure and still save €10mn over the lifetime of the reactor. From these finding, it does seem that the additional cost could be overcome through fuel rotation. There are situations where this might be too difficult, for example military applications where access after two years would be problematic.

## 5. Conclusion

Several different rotational techniques have been examined through variation in operational time and rotation within the core. Through this, the most beneficial was rotating the fuel by 180° after two years, which was modelled to increase the core lifetime by 40.3%. This increase could lead to a fuel cost reduction of up to €30M over the lifetime of the reactor. However, the full economic risks involved in this process have not been covered, but are the focus of a further paper.

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